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APPLICATION

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TITLE: **HIGH FREQUENCY PRESSURE COMPENSATOR**

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High Frequency Pressure Compensator

Background

[0001] Wells are generally drilled into the ground to recover natural deposits of hydrocarbons and other desirable materials trapped in geological formations in the Earth's crust. A well is typically drilled using a drill bit attached to the lower end of a drill string. The well penetrates the subsurface formations containing the trapped materials so that the materials can be recovered.

[0002] During drilling or after a well is drilled, various logging instruments are used to collect information about the formation properties. The well may then be completed based on the information collected about the formation to maximize the production efficiency. In the processes of drilling, logging, completion, and production, various tools are used. These tools need to withstand the harsh conditions downhole, which may include temperatures as high as 200° C and pressures as high as 20,000 psi. Often sensitive parts of the tools are enclosed in chambers (seal housings) that may be filled with liquids (*e.g.*, oil). The part of the tools that exit the enclosed chambers are often protected with seals that isolate the enclosed oil from the outside, while allowing movement (*e.g.*, rotation) of the extruded parts. These seals are often referred to as "dynamic seals" because they seal against a moving part. The following description uses a mud pulse telemetry system as an example to illustrate the present invention.

[0003] FIG. 1 shows a typical drilling system **101**. A drilling rig **102** at the surface is used to rotate a drill bit **107** using a drill string **103**. Using a mud pump **121**, drilling fluid, called "mud," is pumped to the drill bit **107** through the drill string **103**. The downward flow of mud is represented in FIG. 1 by downward arrow **104**. The mud lubricates and cools the drill bit **107** and then it carries the drill

cuttings back to the surface as it flows upwardly through the annulus. The return flow of mud is represented by the upward arrow **106**.

[0004] The drilling system **101** includes a bottom-hole assembly ("BHA") **110** at the bottom end of the drill string **103**. The BHA **110** includes the drill bit **107** and any sensors, testers, tools, or other equipment (not shown) used in the drilling process. Such equipment may include formation evaluation tools, directional drilling tools, and control circuitry.

[0005] Communication between the driller and the BHA **110** is typically called "telemetry." The data that are collected by the sensors in the BHA **110** must be relayed to the surface so that the driller will have the data when making decisions about the drilling process. Additionally, the driller must be able to communicate with the BHA **110** so that commands may be sent to the BHA **110**. A "downlink" is a communication from the surface to the BHA. Likewise, an "uplink" is a communication from the BHA to the surface.

[0006] There are various prior art telemetry methods. One class of telemetry methods is called "mud pulse telemetry." Mud pulse telemetry uses pulses in the mud flow rate or pressure to communicate between the surface and the BHA.

[0007] One method of downlink mud pulse telemetry uses the mud pumps at the surface to control the mud flow rate to the BHA. The flow rate is detected and interpreted by the downlink system. Methods of uplink mud pulse telemetry typically include a pressure modulator in the downhole tool. The pressure modulator creates pressure pulses in the mud flow that may be detected at the surface. A pressure modulator uses a motor or drive mechanism to operate a flow control device to generate pressure pulses in the mud flow. The drive mechanism is enclosed in a seal housing that includes a dynamic seal to allow the drive shaft to exit the seal housing.

[0008] Dynamic seals on downhole tools need to function in a wide range of ambient pressures — from the atmospheric pressure uphole to the high pressure (up to 20,000 psi) downhole. To overcome such challenges, a seal housing is often equipped with a pressure compensation mechanism that permits the pressure inside the seal housing to adapt to the ambient pressure. Prior art pressure compensation mechanisms typically use a piston that is allowed to move in order to change the volume of the seal housing in response to the ambient pressure.

[0009] Due to the limited diameter (hence, the volume) of the downhole tools, the piston mechanism may have to be placed at a distance from the dynamic seal. The distance between the dynamic seal and the pressure compensation mechanism unnecessarily introduces a delay between pressure pulse generation and compensation. It is therefore desirable to have methods and systems that can provide better pressure compensation.

Summary

[0010] In some embodiments the invention relates to a downhole pressure compensation system that includes a seal housing disposed in a downhole tool, a dynamic seal disposed on the seal housing, wherein the dynamic seal seals around a part that is allowed to move relative to the seal housing, and a flexible membrane disposed in a sidewall of the seal housing proximate the dynamic seal.

[0011] In some other embodiments, the invention relates to a method of compensating for a mud pressure signal that includes generating a pressure signal in a mud flow rate, and transmitting the pressure to the inside of a seal housing through a flexible membrane disposed on a seal housing proximate a dynamic seal.

[0012] Other aspects and advantages of the invention will be apparent from the following description and the appended claims.

Brief Description of Drawings

[0013] FIG. 1 shows a cross section of a typical drilling system.

[0014] FIG. 2 shows a cross section of a prior art pressure compensation system.

[0015] FIG. 3A shows one embodiment of a modulator in an open position.

[0016] FIG. 3B shows one embodiment of a modulator in a closed position.

[0017] FIG. 4 shows a cross section of a seal in a prior art pressure compensation system.

[0018] FIG. 5 shows a cross section of a mud port and a piston in a prior art pressure compensation system.

[0019] FIG. 6 shows a graph of a mud pressure signal and a compensated pressure signal in a prior art pressure compensation system at 24 Hz.

[0020] FIG. 7 shows one embodiment of a pressure compensation system in accordance with one embodiment of the invention.

[0021] FIG. 8 shows a graph of a mud pressure signal and a compensated pressure signal in a pressure compensation system operating at 24 Hz in accordance with an embodiment of the invention.

Detailed Description

[0022] Embodiments of the invention relate to pressure compensation systems suitable for applications involving high frequency and high amplitude pressure pulses. Certain embodiments of the present invention relate to a system for high frequency/high amplitude pressure compensation. Other embodiments of the invention may relate to a method of compensating a high frequency/high amplitude pressure signal. For clarity, the following description uses a mud pulse telemetry generator to illustrate the present invention. However, one of ordinary

skill in the art would appreciate that embodiments of the invention are not limited solely to mud pulse generator. Instead, embodiments of the invention are generally applicable in any pressure compensation applications, particularly for downhole tools. The invention will now be described with reference to the figures.

[0023] FIG. 2 shows a cross section of a mud pulse modulator **201** that may be used to send an uplink signal. The mud pulse modulator **201** includes a rotor **202** and a stator **203.** The rotor **202** rotates with respect to the stator **203** to generate the pressure pulses, as will be explained with reference to FIGS. 3A and 3B. The rotor **202** is coupled to a shaft **205** that connects the rotor **202** to a drive assembly that includes a gear assembly **206** and a servo motor **207**. The shaft **205** passes through a seal housing **216**, and seals **204** seal around the shaft **205** to isolate the working oil inside the seal housing **216** from the mud that is outside the seal housing **216**. Typically, a servo motor **207** is used to enable precise control of the rotor **202**, although other drive mechanisms may be used.

[0024] FIGS. 3A and 3B show one example of a modulator **301** that may be used to generate a pressure pulse. In FIG. 3A, the modulator **301** is in an open position. The stator **304** includes four passages, such as passage **305**, that enable mud to flow through the modulator **301**. In the open position, the rotor **306** is positioned so that it does not cover the openings **305** in the stator **304**. The rotor includes cuts **307** that enable the openings **305** to be uncovered in the open position. In the open position, the modulator **301** enables free flow of mud through the modulator **301**.

[0025] FIG. 3B shows a modulator **301** in a closed position. Flaps **308** on the rotor **306** partially cover the openings **305** in the stator **304.** This presents an impediment to the flow of mud, and the pressure increases so that a constant flow rate of mud is maintained. FIGS. 3A and 3B shows the modulator **301** in open and

closed positions, but those having ordinary skill in the art will realize that the rotation of the rotor **306** causes the modulator **301** to modulate between the open and closed positions.

[0026] Referring again to FIG. 2, the seal **204** provides a dynamic seal to isolate the oil inside the seal housing **216** from the mud outside. The oil inside the seal housing **216** lubricates and protects the drive mechanisms. In order for the seal **204** to maintain its integrity and proper function under conditions ranging from the atmospheric pressure (when it is uphole) to the downhole pressure (up to 20,000 psi), a pressure compensation mechanism is needed so that the pressure differential across the seal **204** is minimal, regardless of the outside pressure. The pressure compensation mechanism typically comprises a piston that is able to move freely along a cylinder to alter the volume of the oil chamber in response to the outside pressure, ensuring that the pressures on both sides of the piston are substantially the same regardless of the outside pressure. A pressure compensation mechanism typically used in a downhole tool will be described in detail later.

[0027] Referring to FIG. 2 again, the modulator **201** creates pressure pulses that travel uphole, or to the left in FIG. 2. For example, when the modulator **201** is in a closed position (*e.g.*, as shown in FIG. 3B), a high pressure pulse will travel up hole. In the closed position, a reduction in pressure is experienced on the downhole side of the modulator **201**. Conversely, when the modulator **201** is in an open position (*e.g.*, as shown in FIG. 3A), a reduction in pressure is experienced uphole, and an increase in pressure is experienced on the downhole side of the modulator **201**.

[0028] FIG. 4 shows a close-up of the shaft **205** that drives the rotor (**202** in FIG. 2) and a seal assembly **404, 406** that seal around the shaft **205**. The outer seal **404** is a rotating seal that rotates with the shaft **205**, and inner seal **406** is a stationary

seal that also seals around the shaft **205**, but it remains fixed with the seal housing **216**. In operation, the rotor **202** is driven by the drive shaft **205** to rotate with respect to the stator **203**, generating pressure pulses in the mud. These pressure pulses are experienced on the outboard side of the inner seal **406**, in area **410**, for example. The pressure pulses created by the modulator can have an adverse effect on seal performance and seal life. Thus, it is often desirable to use a pressure compensation system to balance the oil pressure on the inboard side of the seal **406**.

[0029] A pressure compensation system balances the oil pressure inside the seal housing **216** (*i.e.*, in area **412**) so that is will fluctuate with the borehole hydrostatic pressure and the mud pressure signal outside the seal housing **216** (*i.e.*, in area **410**). This will ensure that the pressure differential across the inner seal **406** will remain close to zero at all times. A balanced pressure will reduce the leakage across the seal **406** and, more importantly, increase the life of the seal.

[0030] Referring back to FIG. 2, a pressure compensation system provides pressure compensation using a port **208**, a mud chamber **210**, and a piston **212** to achieve pressure compensation inside the drive housing **209** that is in fluid communication with the stator seal **406**. The piston **212** is free to move along the length of the mud chamber **210** so that the pressures on both sides of the piston **212** are substantially the same, which in turns ensures that the pressures across the stator seal **406** are substantially the same, regardless of the outside pressure. The pressure compensation system is placed at a distance to the seal **406** due to the limited diameter (volume) of the downhole tool. The distance between the pressure compensating piston and the seal **406** necessarily creates a time delay between the pulse generation and compensation. The pressure pulses from the mud pulse modulator **201** need to travel through the mud outside the tool between the modulator **201** and the mud port **208**. At the mud port **208**, the change in pressure may enter the mud chamber **210** in the drive housing **209**. Typically, the

pressure compensation piston **212**, located inside the drive housing **209**, is able to move (*e.g.*, along the length of the mud chamber **210**) in response to pressure differences between the mud in the mud chamber **210** and the oil pressure inside the drive chamber **209**. The oil pressure behind the piston **212** is then relayed to the seal **406** to counter (compensate) the change in pressure on the other side of the seal **406**. However, due to the time needed for the change in pressure to travel this distance, the pressures across the seal **406** are not equalized during the delay. If the pressure on the outside is greater than the pressure on the inside, then the fluid on the outside (*e.g.*, mud) may leak into the oil housing, resulting in damages to the parts to be protected.

[0031] FIG. 5 shows a close-up view of the mud port **208**, the mud chamber **210**, and the pressure compensation piston **212**. A change in pressure enters the drive housing **209** through the port **208** and is transmitted into the mud chamber **210**. The change in pressure then acts on the piston **212**, causing a corresponding change in the oil pressure. An increase in mud pressure will cause the piston **212** to move upwardly and increase the oil pressure. Similarly, a decrease in mud pressure will cause the piston **212** to move downwardly and decrease the oil pressure.

[0032] In some embodiments, a piston **212** may be coupled to a spring **214**. The spring **214** applies a force to the piston **212** that would create a slightly higher pressure in the oil chamber than the pressure in the mud chamber **210**. Thus, if there were to be any leakage across the inner seal (**406** in FIG. 4), the leakage would be of oil out of the seal housing (**216** in FIG. 4) and not of mud into the seal housing.

[0033] Referring again to FIG. 2, an increase of pressure in the mud chamber **210** will cause the piston **212** to move, thereby transmitting the pressure increase through the drive chamber **209** and to the inboard side of the seal (**406** in FIG. 4).

This type of pressure compensation system requires that a pressure pulse travel from the modulator **201** to a port **208** in the drive housing, before returning through the interior of the drive housing **209**.

[0034] The time delay, *t*, between the mud pressure pulse and the resulting pulse in the oil is related to the distance that the pulse must travel and the speed of sound in the particular fluid through which the pulse is traveling. The time delay may be quantified as shown in Equation 1:

$$t = \frac{(d_o + d_m)}{C_m} + \frac{d_m}{C_m} + \frac{d_o}{C_o} \qquad \text{Eq. 1}$$

where d_o is the length of the oil cavity in the tool (shown in FIG. 2), d_m is the length of the mud cavity in the tool (shown in FIG. 2), C_o is the speed of sound in the oil, and C_m is the speed of sound in the mud.

[0035] The first term in Equation 1 represents the time it takes the mud pressure pulse to travel through from the seal and mud pulse modulator area to the mud port (*e.g.*, **208** in FIG. 2). This length is represented by the sum of the length of the oil chamber d_o and the length of the mud chamber d_m. The sum is divided by the speed of sound in mud C_m, the medium through which the signal travels in this direction. The middle term represents the time it takes the pressure pulse to travel back through the mud chamber (*e.g.*, **210** in FIG. 2) inside the drive housing. This time is represented by the length of the mud chamber d_m divided by the speed of sound in mud C_m. The last term in Equation 1 represents the time it takes the pressure pulse to travel through the oil chamber of the drive mechanism — the length of the oil chamber d_o divided by the speed of sound in oil C_o.

[0036] More sophisticated mud pulse telemetry systems use higher pulse frequencies to increase and optimize the data transmission rate of the telemetry system. These can range from less than 1 Hz to 24 Hz. The higher frequencies have created problems with the response time of pressure compensation systems. At higher frequencies, the time that it takes for the pressure signal to travel to the mud port (*e.g.*, **208** in FIG. 2), travel back through the mud chamber (*e.g.*, **210** in FIG. 2), and travel back through the oil chamber to the inboard side of the seal (*e.g.*, **204** in FIG. 2) may be a significant portion of one cycle. The time delay creates a compensated pressure that is out of phase with the modulator pressure.

[0037] FIG. 6 shows a graph of the mud pressure signal **601** along with the compensated pressure signal **602** in the oil on the inboard side of the seal in a prior art pressure compensation system. The signal shown in FIG. 6 is a 24 Hz signal. As shown in FIG. 6, there is a phase shift between the mud signal **601** and the oil signal, or compensated pressure signal **602**. The compensated signal **602** is delayed from the mud signal **601**, making the compensated signal **602** out of phase with the mud signal **601**. The difference between the mud signal **601** and the compensated signal **602** is plotted at **603**. The pressure difference **603** shown in FIG. 6 may cause the seal (*e.g.*, 406 in FIG. 4) to oscillate with the pressure fluctuations (represented by the pressure difference curve **603**). Oscillation of the seal may cause damage to the seal that will reduce seal life. Additionally, when the pressure on the outside of the seal is higher than that on the inside, mud may leak into the housing, leading to damages of the seal and the drive mechanism.

[0038] FIG. 7 shows one embodiment of a pressure compensation system in accordance with one embodiment of the invention. The seal housing **716** includes a flexible membrane **710** that enables pressure to be transmitted to the interior of the seal housing **716**. When the pressure outside of the seal housing **716** increases, the flexible membrane **710** flexes inwardly, thereby increasing the pressure on the inboard side of the seal **706**. Conversely, when the pressure outside of the seal

housing **716** decreases, the flexible membrane **710** flexes outwardly, thereby decreasing the pressure on the inboard side of the seal **706**.

[0039] The flexible membrane **710** is located in the seal housing **716** to be proximate the seal **706**. This significantly reduces the distance over which the pressure signal must be transmitted to compensate the pressure on the inboard side of the seal **706**. By reducing the distance over which the signal must travel, the response time of the pressure compensation system is significantly increased.

[0040] In the embodiment shown, the flexible membrane **710** is coupled to a passageway **712** that leads to the interior of the seal housing **716**. In other embodiments, a flexible membrane may be in contact with both the mud outside the seal housing and with the oil inside the seal housing without the need for a passage way, *i.e.*, the flexible membrane **710** may form part of a wall of a seal housing.

[0041] The flexible membrane **710** may be made of any material that will flex enough to transmit pressure to the interior of the seal chamber **716**. For example, the flexible membrane **710** may be constructed of an elastomer or a thin piece of metal. Additionally, the geometry (*i.e.*, the shape and size) of the membrane **710** may be selected based on the particular application or operating condition. For example, the membrane **710** may extend around the entire circumference of the seal housing **716**, forming a frustoconical shape. In other embodiments, the membrane **710** may form a window over only a portion of the seal housing **716**. The geometry and the material of the membrane **710** may be selected for specific applications and design considerations.

[0042] Those having ordinary skill in the art will realize that any number of variations of a flexible membrane may be possible without departing from the scope of the invention. For example, this description makes reference to a "seal housing," which houses and protects the seals, and a "drive housing," which

houses and protects the drive mechanisms for the modulator. In practice, however, these may not be separate components. That is, a drive mechanism housing may also house and protect the seals.

[0043] Additionally, a flexibly membrane may be constructed of a material having enough strength that the flexible membrane may be in direct contact with both the mud on the outside of the seal housing and the oil on the inside of the seal housing. In such an embodiment, a passage (*i.e.*, passage **712**) between the flexible membrane and the interior of the seal housing may not be necessary. Other variations of a flexible membrane may be devised that do not depart from the scope of the invention.

[0044] FIG. 8 shows a graph of a mud pressure signal **801** along with a compensated pressure signal **802**, using a pressure compensation system in accordance with the invention. The compensated pressure signal **802** closely matches the mud pressure signal **801** created by the modulator (*e.g.*, **202** in FIG. 2). Plot **803** shows the difference between the mud pulse signal **801** and the compensated pressure signal **802**. The difference **803** shows a constant, slight excess pressure on the inside of the seal housing. This slight excess pressure is typically provided by a spring mechanism to ensure that no mud will leak into the housing.

[0045] Embodiments of the invention use flexible members close to the dynamic seals to provide better pressure compensation and improved seal lives. One of ordinary skill in the art would appreciate that the flexible membrane pressure compensation mechanism in accordance with the invention may be used together with the prior art piston pressure compensation mechanism. For downhole tools, the combined use of these two types of pressure compensation mechanisms is particularly beneficial – the piston pressure compensation mechanism ensures that the protected oil chamber can be used in a wide range of pressure (e.g., from the

atmospheric pressure to the downhole pressure), while the flexible membrane mechanism ensures that high frequency and/or high magnitude pressure pulses are effectively compensated.

[0046] It is noted that a piston arrangement is one possible prior art pressure compensation system that could be used with embodiments of the invention. Other pressure compensation systems may include a bellows system or a bladder system. Those having ordinary skill in the art will be able to devise other types of pressure compensation systems that may be used with embodiments of the invention.

[0047] Certain embodiments of the present invention may present one or more of the following advantages. A pressure compensation system in accordance with the invention may decrease the phase shift of a compensated pressure pulse. At a high modulator frequency, the reduced phase shift may reduce the pressure differential across a seal in the modulator system.

[0048] Advantageously, a pressure compensation system in accordance with the invention may reduce or prevent oscillations of a seal in the modulator system. Reduced oscillation may decrease seal leakage and increase seal life. The ability of a pressure compensation system to compensate for high frequency pressure telemetry signals enables the use of still yet higher frequencies in a telemetry. Advantageously, a pressure compensation system in accordance with the invention may enable faster communication in a telemetry system. Similarly, embodiments of the invention may provide benefits to other tools that include pressure compensation mechanisms. It is noted that there are devices that can emit high frequency and high magnitude pressure changes other than the telemetry devices described above and the scope of this invention should not be limited as such.

[0049] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will

appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.